

THE USE OF GPS/MET DATA FOR IONOSPHERIC STUDIES

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LONG-TERM GOAL

Limb sounding of Earth's ionosphere offers a new observation technique for the global ionosphere from low earth orbit (LEO). The GPS/MET proof-of-concept experiment has been successful and several follow-on missions are currently planned. This technology promises to play an important role in realizing the goals of the US Space Weather Program. We are developing techniques to derive global high-resolution 4-D ionospheric electron density fields close to real-time. This may lead to improvements in short-term "Space Weather" prediction.

SCIENTIFIC OBJECTIVES

Space Weather and the state of the ionosphere are of increasing importance to humankind because of their effect on space travel, satellites, electric power grids, and communications. While our "neutral weather" monitoring and prediction capabilities are quite good, "Space Weather" monitoring and prediction is much less advanced. Prediction requires three key components: (a) full understanding of the physics of the ionosphere, (b) knowledge of ionospheric forcing, and (c) good knowledge of the ionospheric state. Our goal is to develop GPS occultation data inversion techniques to obtain accurate global ionospheric electron densities, and thus provide a key parameter of the ionospheric state. Detailed ionospheric monitoring will also help improve our understanding of the fundamental physics that govern ionospheric dynamics.

APPROACH

We use dual frequency GPS carrier phase (L1 and L2) data received in LEO at ~735 km to compute ionospheric electron density profiles (EDP). The standard analysis technique uses the assumption of local spherical symmetry in refractivity (electron density) in the vicinity of the GPS to LEO ray tangent point. This technique is using the Abel transform and is shown to work well under calm ionospheric conditions. In regions with strong electron density gradients the technique can result in large EDP errors and additional gradient information and advanced processing techniques are needed. The required gradient information may be obtained from the Parameterized Ionospheric Model (PIM), the Parameterized Real-time Ionospheric Specification Model (PRISM), or additional data sources. Algorithms are under development to include these constraints in the data inversion. Comparisons with correlative ionosonde data are used to validate both the Abel and the improved inversion techniques.

WORK COMPLETED

First we analyzed hundreds of ionospheric soundings with the standard Abel technique and compared a subset of those results to matching ionosonde data. Next we developed three

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different algorithms to improve GPS/MET EDP by applying PIM as a constraint. The results of the different inversions were compared to ionosonde data to determine the level of improvement.

The Abel inversion technique had been developed under a previous NSF funded study. Three modifications to the Abel inversion were developed, coded and tested under this study. All four algorithms are described briefly below. In addition we began searching our data for evidence of ionospheric scintillation, and present evidence and examples.

The following describes the four algorithms:

1. *Abel inversion:*

This approach is using the assumption of a local spherical symmetry of refractivity (which is proportional to electron density) in the vicinity of tangent points of the rays. The method is expected to provide good results in regions of low horizontal gradients. This processing mode is similar to neutral atmospheric analysis described in the literature (i.e., Melbourne, et al., 1996).

2. *Correction of Abel inversion by direct and inverse simulation with PIM:*

This approach assumes we that have a 1st guess of the electron density field, which reproduces reasonably (in a statistical sense) the horizontal gradients of the true field, although its magnitude may be far from the truth. This 1st guess field is used to compute simulated occultation data, which are inverted with the Abel technique. The assumption is that EDP differences between the 1st guess field and the Abel inversion of the simulated observations provide the vertical structure of the Abel retrieval error of the true observational data. Thus simulated retrieval errors are used to correct inversion results of the true observational data.

For the 1st guess we use PIM at the time and location of the occultation (using representative F10.7 radio fluxes and 3-hr geomagnetic K_p values). When calculating observables for the PIM grid fields, refractive bending is neglected. We specify a 1D grid of PIM electron densities up to 15,000km along each GPS to LEO ray, and apply spline interpolation to calculate TEC. These TECs are converted to (L1-L2) excess phases and inverted with the Abel technique. We denote $N_{abel}^{true}(z)$ to be an EDP retrieved by Abel inversion from the observational data, $N_{abel}^{PIM}(z)$ to be a retrieved profile from the PIM simulated observables, and $N_{local}^{PIM}(z)$ to be a local vertical PIM profile close to the tangent points. Then we apply multiplicative (1) and additive (2) corrections to the Abel inversion of the true observational data (see Figure 1).

$$N_{corr}^{(1)}(z) = N_{abel}^{true}(z) \times \frac{N_{local}^{PIM}(z)}{N_{abel}^{PIM}(z)}$$

$$N_{corr}^{(2)}(z) = N_{abel}^{true}(z) + \frac{\int N_{abel}^{true}(z) dz}{\int N_{abel}^{PIM}(z) dz} [N_{local}^{PIM}(z) - N_{abel}^{PIM}(z)]$$

Figure 1. Abel Inversion to PIM Simulated

When applying the Abel inversion to PIM simulated observables we use zero initialization; i.e. zero calibration of TEC at the top, although simulated TEC accounts for the upper

ionosphere and plasmasphere. Thus this technique should also correct the Abel inversion of the observational data for errors incurred by the zero initialization assumption.

3. *Inversion constrained by horizontal structure of the 1st guess electron density field (PIM):*

This inversion does not use the Abel technique at all. GPS observations are used to adjust the magnitude in each layer of the guess field, while preserving the relative horizontal variations. The technique was implemented very similar to the method described in our 1997 proposal, and we refer to that document for more details.

4. *Variational assimilation of the ionospheric radio occultation data:*

A variational assimilation technique for GPS/MET TEC observations was implemented. The first guess 3D-electron density field is PIM at the time and location of the radio occultation. The approach may be generalized by also including ground based TEC observations, or the use of PRISM. Let \vec{x} to be a vector of state of the ionosphere, i.e. electron density specified on some grid, and let \vec{y} be an observational vector, i.e. TEC observed along a number of rays. Let \hat{H} be an observational operator, i.e. $\vec{y} = \hat{H}\vec{x}$. Let \vec{x}^* be a first guess of the vector of state. Finally let \hat{O} and \hat{B} be the error covariance matrix of the observations, and the covariance matrix of variations of the vector of state respectively. We ignore errors of the observational operator \hat{H} . We solve for the most likely vector of state by minimizing a cost functional:

$$I = (\hat{H}\vec{x} - \vec{y})^T \hat{O}^{-1} (\hat{H}\vec{x} - \vec{y}) + (\vec{x} - \vec{x}^*)^T \hat{B}^{-1} (\vec{x} - \vec{x}^*) = \min$$

The first term in this functional pulls the state vector to fit the TECs observations. The second term pulls it towards the first guess. The balance of these terms depends on the ratio of the observational TEC errors and the magnitude of expected variations of the electron density field. Finite vertical and horizontal correlation distances of expected variations of electron density fields denoted by the matrix \hat{B} stabilize the solution by preventing oscillations with scales much smaller than the correlation distances. Observational errors are assumed uncorrelated (matrix \hat{O} is diagonal). The solution of the problem depends on the first guess \vec{x}^* and the covariance matrix \hat{B} . \vec{x}^* is given by PIM, but \hat{B} is uncertain. One can use a model of \hat{B} with a small number of parameters, which are fit to provide statistically the best possible agreement of the solution with other available observational data. A gaussian model of the matrix \hat{B} with different vertical and horizontal correlation distances l_{ver} and l_{hor} is used:

$$B_{ij} = C^2 N_{fg}(\vec{r}_i) N_{fg}(\vec{r}_j) \exp \left\{ - \left(\frac{r_i - r_j}{l_{ver}} \right)^2 - \left[\frac{r_i + r_j}{2l_{hor}} \arccos \left(\frac{\vec{r}_i \vec{r}_j}{r_i r_j} \right) \right]^2 \right\}$$

where \vec{r}_i and \vec{r}_j are radius vectors of the i -th and j -th elements of the vector of state, $N_{fg}(\vec{r})$ is the 1st guess electron density field, C is the expected relative magnitude of variations of the electron density field. Thus three parameters: C, l_{ver}, l_{hor} need to be fitted.

RESULTS

Figure 1 shows an example Incoherent Scatter Radar (ISR) EDP in comparison with the standard Abel and other techniques using PIM: multiplicative, additive, constrained and variational assimilation methods described above. The variational assimilation results shown in the right panel have been computed for different vertical and horizontal correlation scales of the gaussian covariance matrix. The variational assimilation code is still under development at this time and requires additional tests and improvements.

We processed over 20,000 EDPs and performed a statistical comparison of hundreds of standard Abel inversion profiles with global ionosonde data. As expected, in low gradient regions the Abel inversion provides rather good estimates of f_oF2 and, we assume, of an electron density profile around F2 peak. Over 200 comparisons of GPS/MET minus ionosondes shows -0.3 MHz mean agreement with an rms of 0.8 MHz. We also compared the other PIM constrained inversions (all except the variational assimilation) to the ionosondes for several days. We see that for many occultations the agreement with the ionosondes is considerably improved, while for others there is no improvement or even degradation. Improvements are presumably achieved when the horizontal structure of the true electron density field is close to PIM, and degradation results when it is far from PIM. Unfortunately, the scarcity of ionospheric observational data makes it impossible to explicitly verify this fact. However, we noticed that the number of soundings where PIM constrained retrieval improved the agreement with ionosondes is considerably larger over the U.S. than over Europe. When we ran PIM for 1 day (00,06,12,18 UTC) and compared f_oF2 to ionosondes we noticed that deviations and their spread were approximately twice as large over Europe than over the U.S. This preliminary observation requires further investigation. We will also attempt to run the same tests with improved 1st guess fields from PRISM. Much of our future efforts will be directed towards variational assimilation, as we consider it a more promising method, flexible enough to include other observational data and thus less dependent on the 1st guess.

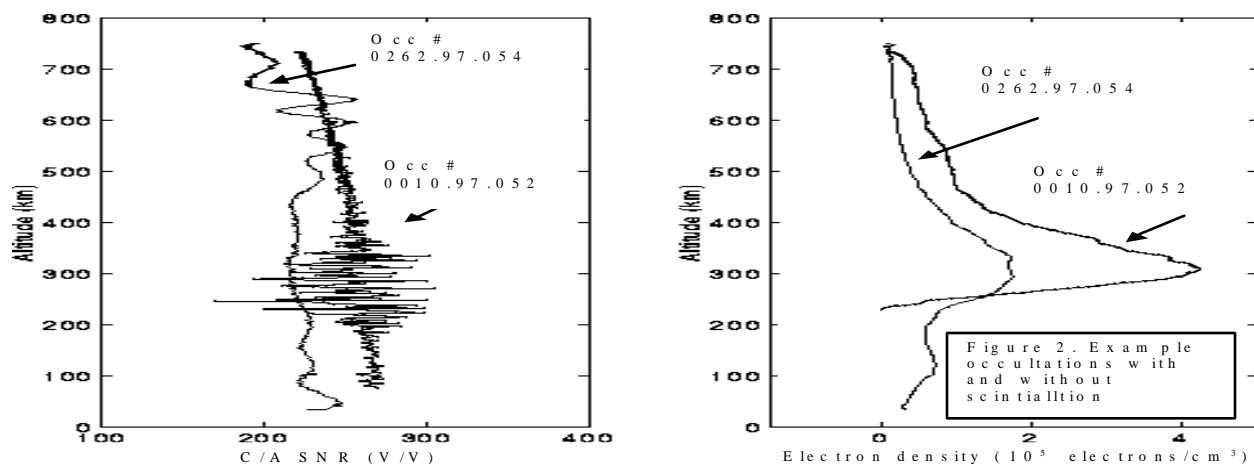


Figure 1. Incoherent Scatter Radar (ISR) EDP Compared with Standard Abel and others using PIM

Scintillation Sensing

The L-band GPS signals received by the GPS/MET receiver are subject to both amplitude and phase ionospheric scintillations. Scintillations predominantly occur between 250 and 400 km in

the post sunset (6pm - 12pm local time) equatorial ionosphere and between 200 and 1000 km at all local times in the polar ionosphere. Scintillation intensities are expected to be the largest at solar maximum, and the smallest at solar minimum.

Figure 2 shows the L1 C/A signal-to-noise ratio (SNR) and EDP (after Abel inversion) for two occultations from February 1997. The first occultation, # 0010.97.052, shows scintillation in the F layer at geodetic latitude and sun-fixed longitude of 7.5 degrees and 163.4 degrees (~ 11pm local time), respectively. This F layer scintillation has an S4 index (defined as the standard deviation of received power divided by the mean value of received power) of 0.018 and an L1 minus L2 phase noise level of 3.3 cm rms. For comparison, the S4 index and phase noise estimate between 600 and 750 km for the same occultation is 0.002 and 0.1 cm rms, respectively. The second occultation, # 0262.97.054, is an example of lower frequency SNR fluctuations, which occur in about 5 % of occultations. These lower frequency fluctuations may be due to ionospheric irregularities or local spacecraft multipath, and are the subject of further study.

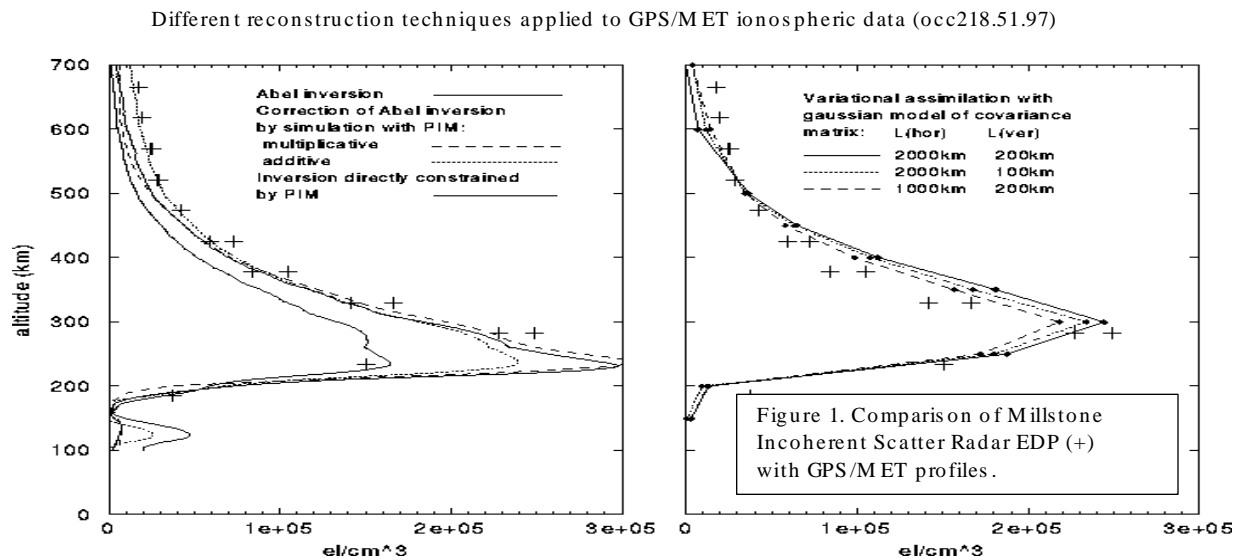


Figure 2. L1 C/A Signal-to-Noise Ratio (SNR) & EDP (after Abel Inversion) for Two Occultations

IMPACT/APPLICATION

New algorithms have been developed to compute EDPs in regions of electron density gradients from occultation data. These algorithms may find operational application in the data analysis of future occultation missions. Result improvement due to these algorithms is not consistent. We believe that this may be due to the quality of PIM, and continuation of the work described here shall use PRISM plus ionospheric data to provide improved 1st guess fields.

We have demonstrated the use of occultation data for the detection of ionospheric scintillation. We are planning to develop techniques that use combined phase and amplitude data to locate inhomogeneities that cause scintillation along the GPS-LEO ray. This may lead to improved definition of regions that cause radio communication problems.

RELATED PROJECTS

Below we list several projects that work on using GPS occultation data. We are providing all of these groups with data and work closely with most of them. The list of projects includes:

1. Ionospheric Studies with GPS/MET data are conducted at Phillips Lab, Hanscom under direction of D. Anderson, and at the Jet propulsion Laboratory by G. Hajj (Hajj *et al.*, 1994);
2. The Danish Meteorological Institute and Saab Ericsson of Sweden are working on the development of software for ionospheric data retrieval in response to a NASA/NOAA/USAF Integrated Program Office (IPO) contract;
3. Rius *et al.* (1997) in Spain developed tomographic techniques that use GPS/MET occultation data and ground based GPS data to determine 4-D electron density fields; and
4. Groups at UCAR, JPL, U. of Arizona, and Stanford U. are working on retrieval of occultation data in the neutral atmosphere.

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